

Relations between Microwave Bursts and near-Earth High-Energy Proton Enhancements and their Origin

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Abstract We further study the relations between parameters of bursts at 35 GHz recorded with the Nobeyama Radio Polarimeters during 25 years, on the one hand, and solar proton events, on the other hand (Grechnev et al. 2013: PASJ 65, SP1, S4). Here we address the relations between the microwave fluences at 35 GHz and near-Earth proton fluences above 100 MeV in order to find information on their sources and evaluate their diagnostic potential. A correlation was found to be pronouncedly higher between the microwave and proton fluences than between their peak fluxes. This fact probably reflects a dependence of the total number of protons on the duration of the acceleration process. In events with strong flares, the correlation coefficients of high-energy proton fluences with microwave and soft X-ray fluences are higher than those with the speeds of coronal mass ejections. The results indicate a statistically larger contribution of flare processes to high-energy proton fluxes. Acceleration by shock waves seems to be less important at high energies in events associated with strong flares, although its contribution is probable and possibly prevails in weaker events. The probability of a detectable proton enhancement was found to directly depend on the peak flux, duration, and fluence of the 35 GHz burst, while the role of the Big Flare Syndrome might be overestimated previously. Empirical diagnostic relations are proposed.

Keywords: Solar Proton Events; Microwave Bursts; Big Flare Syndrome; SEP Diagnostics

1. Introduction

The problems of the origin of solar proton events (SPEs) and their diagnostics are hotly debated over almost half a century. Two concepts of their origin are

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considered and even contrasted (see, *e.g.*, Kallenrode, 2003; Grechnev *et al.*, 2008; Aschwanden, 2012; Reames, 2013; Trotter *et al.*, 2015 for a review and references). The flare-acceleration concept relates the SPE sources to flare processes in coronal magnetic fields of active regions, manifested particularly in X-ray and microwave emissions. The shock-acceleration concept relates the major SPE sources to bow shocks driven by fast coronal mass ejections (CMEs).

There are convincing arguments in favor of both the flare and shock origin of SPEs. Gamma-rays concurrent with other flare emissions favor the hypothesis of acceleration of heavy particles in flares simultaneously with electrons (see, *e.g.*, Chupp and Ryan, 2009; Vilmer, MacKinnon, and Hurford, 2011). On the other hand, *in situ* measurements of the particle composition, such as the iron charge state, Fe/O ratio, and others appear to favor the shock-acceleration of ions at normal coronal temperatures (see, *e.g.*, Reames, 2013). Note that such measurements are limited to moderate ion energies, while acceleration of heavier ions is indeed more effective by Fermi mechanisms operating in shock-acceleration. The apparent delay of the particle escape near the Sun (Reames, 2009, 2013) does not seem to be a reliable indication of their exceptional shock-acceleration, because trapped flare-accelerated particles can escape from closed coronal structures after their delayed reconnection with open structures in the course of the CME expansion (Masson *et al.*, 2012; Grechnev *et al.*, 2013b). It is also possible that the alternative concepts are based on different observations subjected to selection effects.

The sources of the particle acceleration in flares and by shock waves are considered to be remote and independent of each other. The concepts of their origin are mainly based on hypotheses proposed in past decades, when opportunities to observe solar phenomena were much poorer than now. The well-known fact of a reduced proton productivity of short-duration events (referring to the soft X-ray (SXR) emission) led to a hypothesis about predominance of different acceleration mechanisms in ‘impulsive’ and ‘gradual’ events (see, *e.g.*, Croom, 1971; Cliver *et al.*, 1989; Reames, 2009, 2013; and references therein).

However, recent observational studies have revealed a closer association between solar eruptions, flares, shock waves and CMEs, than previously assumed. It was found that the CME acceleration pulse occurs almost simultaneously with hard X-ray and microwave bursts (Zhang *et al.*, 2001; Temmer *et al.*, 2008, 2010). The helical component of the CME’s flux rope responsible for its acceleration is formed by reconnection which also causes a flare (Qiu *et al.*, 2007). A detailed quantitative correspondence has been established between the reconnected magnetic flux and the rate of the flare energy release (Miklenic, Veronig, and Vršnak, 2009). ■ Most likely, a shock wave is typically excited by an erupting flux rope as an impulsive piston inside a developing CME during the rise phase of the hard X-ray and microwave bursts (Grechnev *et al.*, 2011, 2013a). Then the shock wave detaches from the piston and quasi-freely propagates afterwards like a decelerating blast wave. Its transition to the bow-shock regime is possible later, if the CME is fast (Grechnev *et al.*, 2015). Thus, parameters of the CME and shock wave should be related to those of a corresponding flare, and the traditional contrasting of the acceleration in a flare and by a shock might be exaggerated. Some aspects of the correspondence between the parameters of flares, CMEs,

shock waves, and SPEs have been stated by Nitta, Cliver, and Tylka (2003) and Gopalswamy *et al.* (2012).

By taking account of recent results, one can expect a correspondence between the parameters of SPEs and microwave bursts. Indeed, the correlation between SPEs and strong high-frequency radio bursts has been known for many decades (*e.g.*, Croom, 1971; Castelli and Barron, 1977; Akinian *et al.*, 1978; Cliver *et al.*, 1989, Melnikov *et al.*, 1991). Alternatively, Kahler (1982), advocating the shock-related origin of SPEs, explained this association by the ‘Big Flare Syndrome’ (BFS), *i.e.*, a general correspondence between the energy release in an eruptive flare and its various manifestations. Thus, different flare parameters should correlate with each other regardless of any physical connection between them. The basic concept is clear, while the measure of the degree of correlation due to the BFS used by Kahler (1982) does not seem to be obvious. Assuming a single source for accelerated protons and heavier ions, he concluded that normal coronal temperatures of the ions ruled out the flare-related origin of the protons. Thus, the correlation with the thermal soft X-ray flux (1–8 Å) was considered as a measure of the BFS contribution. On the other hand, the mentioned reasons indicate the origins of protons in both flare-related and shock-related accelerators, whose efficiency can be largely different for different particles. It is difficult, if possible, to distinguish between different sources of the protons. For these reasons, Kahler (1982) might have somewhat overestimated the role of the BFS. A number of later studies interpreting observational results in terms of traditional hypotheses apparently supported the shock-acceleration concept (*e.g.*, Tylka *et al.*, 2005; Rouillard *et al.*, 2012, and others), that have led to an underestimation of diagnostic opportunities of microwave bursts. Nevertheless, it seems worth to analyze the relations between flare microwave bursts and SPEs, irrespective of their origin.

These relations were considered previously in a number of studies, but mostly at frequencies < 17 GHz (see, *e.g.*, Akinian *et al.*, 1978; Cliver *et al.*, 1989). These relatively low frequencies can belong to either the optically thin or thick branch of the gyrosynchrotron spectrum, causing the ambiguity of the results and complicating their interpretation. This difficulty was overcome by Chertok, Grechnev, and Meshalkina (2009) through measuring microwave fluxes at two different frequencies.

Microwave emissions at higher frequencies in the optically thin regime seem to be most sensitive to large numbers of high-energy electrons gyrating in strong magnetic fields, being thus directly related to the energy release rate in the flare–CME formation process during its main (impulsive) phase. The frequency of 35 GHz is the highest one, at which stable long-term observations are available, thanks to the operation of the Nobeyama Radio Polarimeters (NoRP; Nakajima *et al.*, 1985). All of these circumstances determined our choice of the analyzed data.

In our previous study (Grechnev *et al.*, 2013b), we mainly analyzed the relations between peak fluxes at 35 GHz, $F_{35} \geq 10^3$ sfu ($1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), recorded with NoRP since 1990 to 2012, on the one hand, and peak fluxes of SPEs > 100 MeV, J_{100} , on the other hand. Most events showed a scattered direct tendency between the microwave and proton peak fluxes. Considerable

SPEs were revealed even after east solar sources, if the microwave bursts were strong enough.

A better correspondence might exist between some combinations of the time-integrals (fluences) of proton fluxes and microwave bursts (see, *e.g.*, Kahler, 1982; Chertok, 1990; Trottet *et al.*, 2015). In this study we consider these combinations.

An additional aspect of our analysis was inspired by a recent study of Trottet *et al.* (2015), who analyzed the correlations between proton fluxes in a range of 15–40 MeV and parameters characterizing flares and CMEs. Their analysis revealed significant correlations between the peak proton flux, on the one hand, and the start-to-peak SXR fluence and CME speed, on the other hand. Neither the microwave fluence nor the SXR peak flux provided significant contribution to the total correlations. The results indicate that both flare-accelerated and shock-accelerated protons contribute to near-Earth fluxes in this energy range. Trottet *et al.* (2015) and Dierckxsens *et al.* (2015) revealed indications at the domination of shock-acceleration for protons with energies below 10–20 MeV and flare-acceleration for higher energies, but the statistical significance of this finding was insufficient. Our data set allows us verifying this statement.

Our aim in this respect is not advocating either of the concepts of the SPE origin. We try instead to understand how the results of our analysis as well as those of different studies (sometimes seemingly incompatible) could be reconciled with each other to form a probable consistent picture. In the course of our study, we endeavor to find what the 35 GHz radio bursts can tell us about SPEs, to reveal diagnostic opportunities of these radio bursts to promptly estimate a probable importance of a forthcoming high-energy SPE, and to highlight promising ways to further investigate into the SPE problem.

A number of mentioned studies considered a sample of SPEs selected by some criteria and analyzed parameters of responsible solar eruptive events. Our reverse approach misses many SPEs after weaker bursts, but it is natural for the diagnostic purposes and promises understanding how parameters of microwave bursts are related with the proton productivity of solar events.

Section 2 considers statistical relations between the peak flux and duration of the 35 GHz burst and the probability of a proton enhancement, as well as between the microwave and proton fluences. Section 3 analyzes correlations between proton fluences and parameters characterizing flares and shock waves, and examines which of these correlations are significant. Section 4 discusses the results and presents the main conclusions.

2. Statistical Analysis of Parameters of Microwave Bursts and Proton Fluxes > 100 MeV

2.1. Data

Data lists of microwave bursts recorded by NoRP are posted on the Web site <http://solar.nro.nao.ac.jp/norp/html/event/>. We considered all microwave bursts with peak flux densities at 35 GHz $F_{35} \geq 10^3$ sfu. This criterion has selected

104 bursts. We also looked for proton enhancements (*e.g.*, Kurt *et al.*, 2004) with peak fluxes $J_{100} > 10$ pfu ($1 \text{ pfu} = 1 \text{ particle cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) not to miss big SPEs after weaker microwave bursts, and revealed seven additional events. Three of them were caused by backside sources, whose microwave emission could not reach Earth. No conclusions can be drawn about these events, and they were excluded from further analysis. Four large SPEs occurred after moderate microwave bursts with $F_{35} < 10^3$ sfu. Two of them caused ground level enhancements of cosmic ray intensity (GLEs): 2000-11-08, 2001-12-26 (GLE63), 2002-04-21, and 2012-05-17 (GLE71).

Automatically processed digital NoRP data in the XDR (IDLsave) format are accessible via <ftp://solar-pub.nao.ac.jp/pub/nsro/norp/xdr/>. The technique to accurately process NoRP data and to evaluate quantitative parameters of the bursts is described in Grechnev *et al.* (2013b). For each event we recalibrated the pre-burst level, which was often not perfect. This constant level was subtracted in calculating total microwave fluences. The contribution of the thermal bremsstrahlung was estimated from SXR GOES data for four mentioned proton-abundant events. It was 42% for the 2000-11-08 event, 31% for 2012-05-17, 19% for 2002-04-21, and 18% for 2001-12-26. The thermal contribution to the remaining stronger bursts with peak fluxes $F_{35} \geq 1000$ sfu was neglected.

Digital data of GOES proton monitors are available at http://satdat.ngdc.noaa.gov/sem/goes/data/new_avg. The total proton fluences were calculated for the integral proton channel $E_p > 100$ MeV for the whole time of a proton enhancement with subtraction of a constant background level. If an SPE overlapped with a decay of a preceding event, then the background was fit with an exponential function.

The data on events with the analyzed microwave bursts, corresponding proton enhancements, CMEs, and calculated parameters are presented in Table 1. The events are categorized according to their peak fluxes at 35 GHz, F_{35} , similar to the GOES classification. These are mX (microwave-eXtreme, $F_{35} > 10^4$ sfu), mS (microwave-Strong, $10^3 \text{ sfu} < F_{35} < 10^4$ sfu), mM (microwave-Moderate, $10^2 \text{ sfu} < F_{35} < 10^3$ sfu). The behind-the-limb events, whose microwave emission could not be detected, are categorized as mO (microwave-Occulted) events.

The list of events presented by Grechnev *et al.* (2013b) was supplemented with events since late 2012 to March 2015 and events 93 and 94, missing in the NoRP Event List. A number of typos have been corrected. The table is supplemented with the calculated total microwave and proton fluences, start-to-peak SXR fluences, and the CME speeds, if known. They were taken from the on-line CME catalog (Yashiro, 2004; http://cdaw.gsfc.nasa.gov/CME_list/) containing the measurements from SOHO/LASCO data (Brueckner *et al.*, 1995). An atypical event 5 (SOL1991-05-18), previously assessed as a non-SPE, was reconsidered. This long-duration mX event was associated with an X2.8 flare, type IV and II bursts (*i.e.*, a CME and shock wave); thus, an SPE is expected in any case. Unlike an apparently well-connected position (N32W87), a related SPE had a long-lasting rise of more than half a day (Sladkova *et al.*, 1998) typical of events with far-east sources. Chertok, Grechnev, and Meshalkina (2009) assumed an unfavorable connection between its source and Earth that is supported by the occurrence of a geomagnetic storm on 17–19 May with Dst up to -105 nT (http://wdc.kugi.kyoto-u.ac.jp/dst_final/199105/index.html).

Table 1. Analyzed events

No	Date	T_{peak}	GOES class	Flare Φ_{SXR} 10^{-3} J m^{-2}	Position	Microwave burst				Protons near Earth			V_{CME}
						Δt_{35} min	F_{35} 10^3 sfu	Φ_{35} 10^5 sfu s	J_{100} pfu	Φ_{100} 10^3 pfu s	J_{10} pfu	δ_{p}	km s $^{-1}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
mX events with extreme fluxes at 35 GHz ($F_{35} > 10^4 \text{ sfu}$)													
1	1990-04-15	02:55	X1.4	190	N32E54	66	20	202	0.04	4	9	2.35	U
2	1990-05-21	22:17	X5.5	120	N34W37	7	38	45	18	560	300	1.22 ¹	U
3	1991-03-22	22:45	X9.4	200	S26E28	2	122	65	55	1300	28000	2.70	U
4	1991-03-29	06:48	X2.4	70	S28W60	7	11	10	0	0	20	U	U
5	1991-05-18	05:46	X2.8	470	N32W87	26	21	143	0.05	3.3	7	2.14	U
6	1991-06-04	03:41	X12	1060	N30E60	15	130 ²	470 ²	2	90	50	1.40	U
7	1991-06-06	01:12	X12	750	N33E44	17	130 ²	890 ²	2.5	569	200	1.90	U
8	1991-06-09	01:40	X10	310	N34E04	7	74	87	1.2	17	80	1.82	U
9	1991-06-11	02:06	X12	500	N32W15	18	46	159	168	2200	3000	1.25 ¹	U
10	1991-10-24	02:41	X2.1	35	S15E60	0.6	34	6.4	0	0	0	U	U
11	1992-11-02	03:08	X9.0	530	S23W90	15	41	195	70	2900	800	1.06 ¹	U
12	2001-04-02	21:51	X17	930	N18W82	6	25	38	4.8	220	380	1.90	2505
13	2002-07-23	00:35	X4.8	210	S13E72	17	15	51	0	0	0	U	2285
14	2002-08-24	01:12	X3.1	178	S02W81	16	11	46	27	400	220	0.91 ¹	1913
15	2004-11-10	02:13	X2.5	80	N09W49	7 ²	10 ²	15 ²	2	71	75	1.57	3387
16	2005-01-20	07:01	X7.1	500	N12W58	25	85	370	680	6400	1800	0.42 ¹	2800 ³
17	2006-12-13	02:40	X3.4	310	S06W24	31	14	32	88	1900	695	0.89 ¹	1774
18	2012-03-07	00:24	X5.4	310	N17E15	80	11	136	67	5300	1500	1.35	2684
19	2012-07-06	23:08	X1.1	12	S15W63	3	17	12	0.27	7.2	22	1.91	1828
20	2014-02-25	00:49	X4.9	110	S12E82	16	48	76	0.8	102.5	19	1.38	2147
mS events with strong fluxes at 35 GHz ($10^3 \text{ sfu} < F_{35} < 10^4 \text{ sfu}$)													
21	1990-05-11	05:48	X2.4	70	N15E13	14	2.0	1.8	0	0	0	U	U
22	1990-05-21	01:25	M4.8	20	N33W30	7	1.3	0.6	U	U	U	U	U

Table 1. (Continued)

No	Date	T_{peak}	GOES class	Flare Φ_{SXR} 10^{-3} J m^{-2}	Position	Microwave burst Δt_{35} min	F_{35} 10^3 sfu	Φ_{35} 10^5 sfu s	J_{100} pfu	Protons near Earth Φ_{100} 10^3 pfu s	J_{10} pfu	δ_{p}	V_{CME} km s^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
23	1990-05-23	04:20	M8.7	50	N33W55	10	1.0	1.5	0	0	0	U	U
24	1990-06-10	07:27	M2.3	7	N10W10	3	1.0	0.8	0	0	0	U	U
25	1991-01-25	06:30	X10	250	S12E90	6	9.4	13	0.14	13	1	0.85	U
26	1991-03-05	23:26	M6.2	7	S23E79	2	1.4	0.6	0	0	0	U	U
27	1991-03-07	07:49	X5.5	15	S20E62	3	2.0	1.5	0.08	1	0.7	0.94	U
28	1991-03-13	08:04	X1.3	40	S11E43	2	3.6	0.9	0.03	0.2	4.6	2.18	U
29	1991-03-16	00:50	X1.8	40	S10E09	3	3.2	0.4	0	0	0	U	U
30	1991-03-16	21:56	M6.0	20	S09W04	4	1.6	0.2	0	0	0	U	U
31	1991-03-19	01:58	M6.7	8	S10W33	1	7.2	1.9	0	0	0	U	U
32	1991-03-21	23:43	M5.4	17	S25E40	3	7.2	3.4	0	0	0	U	U
33	1991-03-23	22:18	M5.6	30	S25E16	15	1.7	1.1	U	U	U	U	U
34	1991-03-25	00:22	X1.1	50	S26E01	11	3.9	8.8	0	0	0	U	U
35	1991-03-25	08:18	X5.3	150	S25W03	4	4.2	4.1	0.5	6	150	2.47	U
36	1991-05-16	06:54	M8.9	60	N30W56	9	8.0	11	U	U	U	U	U
37	1991-05-29	23:43	X1.0	20	N05E38	1	1.7	0.4	U	U	0.8	U	U
38	1991-06-30	03:01	M5.0	20	S06W19	0.8	2.0	0.2	0	0	0	U	U
39	1991-07-30	07:12	M7.2	6	N14W58	0.9	2.0	0.3	0	0	0	U	U
40	1991-07-31	00:53	X2.3	70	S17E11	5	1.6	1.6	0	0	0	U	U
41	1991-08-02	03:16	X1.5	50	N25E15	8	1.2	2.7	0	0	0	U	U
42	1991-08-03	01:23	M2.9	2.6	N24E05	3	2.8	0.8	0	0	0	U	U
43	1991-08-25	00:49	X2.1	260	N24E77	29	1.4	10	0.03	1.1	21	2.84	U
44	1991-10-27	05:49	X6.1	150	S13E15	6	8.8	13	0	0	40	U	U
45	1991-11-02	06:47	M9.1	22	S13W61	3	1.4	0.5	0	0	0.3	U	U
46	1991-11-15	22:38	X1.5	50	S13W19	4	1.5	1.2	0.28	2.6	1.1	0.59	U

Relations between microwave bursts and high-energy protons

Table 1. (Continued)

No	Date	T_{peak}	GOES class	Flare Φ_{SXR} 10^{-3} J m^{-2}	Position	Microwave burst Δt_{35} min	F_{35} 10^3 sfu	Φ_{35} 10^5 sfu s	J_{100} pfu	Protons near Earth Φ_{100} 10^3 pfu s	J_{10} pfu	δ_{p}	V_{CME} km s^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
47	1992-02-14	23:09	M7.0	15	S12E02	1	1.0	0.3	0	0	0	U	U
48	1992-02-27	08:11	C2.6	0.2	N03W05	0.6	1.0	0.1	0	0	0	U	U
49	1992-06-28	05:15	X1.8	170	N11W90	14	1.3	7.5	0.22	1.6	14	1.80	U
50	1994-01-16	23:25	M6.1	30	N07E71	9	1.2	1.1	0	0	0	U	U
51	1997-11-04	05:58	X2.1	26	S14W33	3	1.0	0.7	2.3	59	72	1.50	785
52	1998-08-08	03:17	M3.0	2	N14E72	0.7	2.0	0.5	0	0	0	U	U
53	1998-08-22	00:01	M9.0	30	N42E51	6	1.0	1.7	U	U	2.5	U	U
54	1998-11-22	06:42	X3.7	100	S27W82	7	6.7	5.5	0.22	1.5	4	1.26	U
55	1999-08-20	23:08	M9.8	7	S23E60	1	3.0	0.6	0	0	0	U	812
56	1999-12-28	00:48	X4.5	100	N23W47	2	2.2	1.2	0.1	0.5	0.5	0.69	672
57	2000-09-30	23:21	X1.2	30	N09W75	4	5.3	2.3	0	0	0	U	C
58	2000-11-24	05:02	X2.0	38	N19W05	2	9.3	5.6	0.58	32	8	1.13	1289
59	2001-03-10	04:05	X6.7	7	N26W42	1	1.7	0.3	0	0	0.2	U	819
60	2001-04-03	03:57	X1.2	146	S21E71	31	2.9	19	0	0	U	U	1613
61	2001-04-10	05:26	X2.3	100	S24W05	30	3.0	28	0.47	15	100	2.32	2411
62	2001-10-12	03:27	C7.6	1	N16E70	1	1.3	0.3	0	0	0	U	U
63	2001-10-25	05:21	C5.2	0.4	S19W17	1	1.2	0.3	0	0	1	U	C
64	2002-02-20	06:12	M5.1	16	N13W68	5	1.5	0.9	0.1	0.3	10	2.00	952
65	2002-07-18	03:37	M2.2	5	N19W27	2	1.4	0.3	0	0	0	U	C
66	2002-08-20	01:40	M5.0	5	S08W34	0.5	1.8	0.1	0	0	0	U	961
67	2002-08-21	01:41	M1.4	2	S10W47	1	1.3	0.1	0	0	0	U	400
68	2002-08-21	05:34	X1.0	10	S09W50	0.7	1.4	0.3	0	0	0	U	268
69	2003-04-26	00:58	M2.1	2.2	N20W65	2	2.2	0.4	0	0	0	U	690
70	2003-04-26	03:06	M2.1	2.4	N20W69	0.3	2.4	0.1	0	0	0	U	289

Table 1. (Continued)

No	Date	T_{peak}	GOES class	Flare Φ_{SXR} 10^{-3} J m^{-2}	Position	Microwave burst			Protons near Earth			δ_{p}	V_{CME}
(1)	(2)	(3)	(4)	(5)	(6)	Δt_{35} min	F_{35} 10^3 sfu	Φ_{35} 10^5 sfu s	J_{100} pfu	Φ_{100} 10^3 pfu s	J_{10} pfu	(13)	km s $^{-1}$ (14)
71	2003-05-28	00:27	X3.6	130	S08W22	14	3.5	10	0.15	2.6	121	2.90	1366
72	2003-05-29	01:05	X1.2	40	S07W31	12	1.2	3.4	0.03	1.3	2	1.82	1237
73	2003-05-31	02:29	M9.3	21	S06W60	8	3.5	13	0.8	16	27	1.53	1835
74	2003-06-15	23:56	X1.3	70	S07E80	8	1.9	5.8	0	0	0	U	2053
75	2003-06-17	22:55	M6.8	40	S08E58	23	1.8	1.5	0	0	0	U	1813
76	2003-10-24	02:54	M7.6	70	S19E72	32	3.9	28	0	0	0	U	1055
77	2003-10-26	06:54	X1.2	160	S17E42	62	3.6	20	0	0	0	U	1371
78	2004-01-06	06:29	M5.8	15	N05E89	8	1.0	2.3	0	0	0	U	1469
79	2004-01-07	04:04	M4.5	23	N02E82	9	1.8	4.4	0	0	0	U	1581
80	2004-07-16	02:06	X1.3	25	S10E39	5	1.5	1.1	0	0	0	U	154
81	2004-08-14	05:44	M7.4	11	S12W29	7	1.0	0.4	0	0	0	U	307
82	2004-10-30	06:18	M4.2	7	N13W21	7	1.3	0.7	0.04	0.3	0.9	1.35	422
83	2004-11-03	03:35	M1.6	6	N07E46	10	1.0	3.2	0	0	0.4	U	918
84	2005-01-01	00:31	X1.7	40	N04E35	6	1.7	3.0	0	0	0	U	832
85	2005-01-15	00:43	X1.2	25	N13E05	6	3.3	1.5	0	0	0	U	C
86	2005-07-30	06:35	X1.3	100	N11E58	27	1.2	5.1	0	0	0	U	1968
87	2005-08-25	04:44	M6.4	10	N08E82	5	4.3	5.1	0	0	0	U	1327
88	2005-09-13	23:22	X1.7	33	S11E10	6	5.0	1.3	0.05	1	200	3.6	999 ⁵
89	2005-09-17	06:05	M9.8	20	S11W41	6	1.3	1.8	0	0	1.4	U	C
90	2010-06-12	00:57	M2.0	4	N24W47	2 ²	4.0 ²	2.7 ²	0.05	0.26	0.9	1.26	486
91	2011-08-04	03:57	M9.3	26	N16W49	11	1.4	3.4	1.5	28	77	1.71	1315
92	2011-08-09	08:05	X6.9	86	N17W83	6	1.0	4.4	2.5	22	22	0.94	1610
93 ⁴	2011-09-06	22:20	X2.2	50	N14W18	2	3.0	5.5	0.5	8.2	10	1.30	575
94 ⁴	2011-09-07	22:37	X1.7	44	N14W28	2	1.0	4.6	0.05	1.3	10	2.30	792

Relations between microwave bursts and high-energy protons

Table 1. (*Continued*)

No	Date	T_{peak}	GOES class	Flare Φ_{SXR} 10^{-3} J m^{-2}	Position	Microwave burst			Protons near Earth				V_{CME}
						Δt_{35} min	F_{35} 10^3 sfu	Φ_{35} 10^5 sfu s	J_{100} pfu	Φ_{100} 10^3 pfu s	J_{10} pfu	δ_{p}	km s^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
95	2012-01-23	03:59	M8.7	60	N29W36	39	2.2	24	2.3	85	2700	3.07	2175
96	2012-10-23	03:17	X1.8	40	S13E58	3	4.4	1.5	0	0	0	U	C
97	2013-05-13	02:17	X1.7	130	N10E89	18	1.2	5.2	0	0	0	U	1270
98	2013-05-14	01:11	X3.2	100	N11E74	22	1.1	0.6	0.03	0.12	1	1.52	2625
99	2013-10-28	01:59	X1.0	61	N04W66	8	1.9	2.6	0.12	7	5	1.62	695
100	2013-11-08	04:26	X1.1	20	S44E86	4	4.0	3.0	0	0	0.7	U	497
101	2014-10-22	01:59	M8.7	80	S12E21	8	1.6	7.8	0	0	0	U	C
102	2014-10-30	00:37	M1.3	20	S14W81	1.1	1.4	0.2	0	0	0	U	C
103	2014-12-20	00:28	X1.8	83	S18W28	6	1.0	5.2	0	0	1.5	U	U
104	2015-03-10	03:24	M5.1	12	S16E34	4.2	2.0	0.5	0	0	0	U	U
mM events with strong proton fluxes ($J_{100} > 10 \text{ pfu}$, $10^2 \text{ sfu} < F_{35} < 10^3 \text{ sfu}$)													
105	2000-11-08	23:28	M7.8	66	N10W75	53	0.09	2.1	320	13000	14000	1.64	1738
106	2001-12-26	05:40	M7.1	110	N08W54	26	0.78	8.2	47	600	700	1.17 ¹	1446
107	2002-04-21	01:51	X1.5	280	S14W84	120	0.5 ²	7.2 ²	20	1500	2000	2.0	2393
108	2012-05-17	01:47	M5.1	31	N09W74	17	0.2	1.7	18	305	230	1.11 ¹	1582
mO backside events with strong proton fluxes ($J_{100} > 10 \text{ pfu}$)													
109	1990-05-28	04:33	U	0	N36W120	U	U	U	4.5	295	44	0.99 ¹	U
110	2001-04-18	02:14	C2.2	45	S20W115	U	U	U	12	270	230	1.28 ¹	2465
111	2001-08-15	23:50	U	0	N01W120	U	U	U	27	670	470	1.24	1575

¹GLE event²Estimated from different data³A compromise between the estimates of Gopalswamy *et al.* (2005) and Grechnev *et al.* (2008)⁴Missing in the NoRP event list⁵Excluded from the analysis because of overlap with a preceding event

Column (1) of Table 1 presents the event number. Columns (2) and (3) show the date and time of the flare peak according to GOES reports. Columns (4)–(6) contain GOES class, start-to-peak SXR fluence, and flare coordinate.

Columns (7)–(9) list the half-height duration, peak intensity, and total microwave fluence at 35 GHz, Φ_{35} . NoRP records at 35 GHz were absent or damaged for some events. In such cases, the value of F_{35} was estimated by means of interpolation from the adjacent frequencies of 17 and 80 GHz and/or from the 34 GHz data of the Nobeyama Radioheliograph (NoRH; Nakajima *et al.*, 1994).

Columns (10)–(13) list parameters of near-Earth proton enhancements: the peak flux of protons with energies above 100 MeV, J_{100} ; the total fluence, Φ_{100} ; the peak flux of protons with energies above 10 MeV, J_{10} ; the index of the integral energy proton spectrum, $\delta_p = \log_{10}(J_{10}/J_{100})$, which was calculated from the peak fluxes of protons with different energies occurring at different times, thus attempting to take account of their velocity dispersion. The events marked in column (13) with a superscript ⁽¹⁾ were associated with GLEs. Column (14) presents the CME speed. Unknown or uncertain parameters are denoted by ‘U’. Confined flares are denoted by ‘C’.

The data from Table 1 are shown in Figure 1a, similar to a corresponding figure in Grechnev *et al.* (2013b). For clarity, solar events are categorized according to their heliolongitude, λ , into three intervals with boundaries of -30° and $+20^\circ$, presented by the colored circles. The events without detectable proton fluxes are shown at the horizontal dotted line below, to reveal their amount. The majority of SPEs is grouped between the slanted lines $(F_{35}/1100)^2$ and $(F_{35}/13000)^2$ pfu, forming the ‘main sequence’. Four atypical proton-abundant mM events denoted by the black squares reside in the upper-left part of the figure, much higher than the ‘main sequence’. The correlation coefficients between the logarithms of the peak values of the microwave and proton fluxes for all events, ρ_{All} , and separately for west events only, with a heliolongitude $\lambda > 20^\circ$, ρ_{West} , are shown in the upper part of the figure. The correlation for the west events is lower due to a considerable contribution from the four abundant events, all of which had west locations, while only 60% of all SPEs had sources with $\lambda > 20^\circ$.

Following Kahler (1982), we show in Figure 1b the same events, but with a correction $\exp\{[(\lambda - 54^\circ)/63]^2\}$ for the longitudinal dependence of > 100 MeV protons (Belov, 2009). This dependence is close to the result of Lario *et al.* (2013) obtained for protons in an energy range of 25–53 MeV. The correction was formally applied to all events, including west events. The strongest effect of the correction is for far-east events (open circles), and somewhat weaker effect is for moderately east events (gray filled circles). The usage of the longitudinal correction increases the correlation for the whole ensemble of events by 70%. We therefore apply this correction in further analysis to all parameters of proton enhancements, even if their solar sources had west locations. Since this correction is uncertain, we additionally considered the correlation coefficients for west events only.

It is not obvious how to handle the atypical event 5. It is an outlier with its actual longitude (the slanted cross in Figure 1a). According to its properties, event 5 should be handled in a way similar to the east events, but a suitable correction is unknown. As a tolerable, but practically inappropriate compromise, we

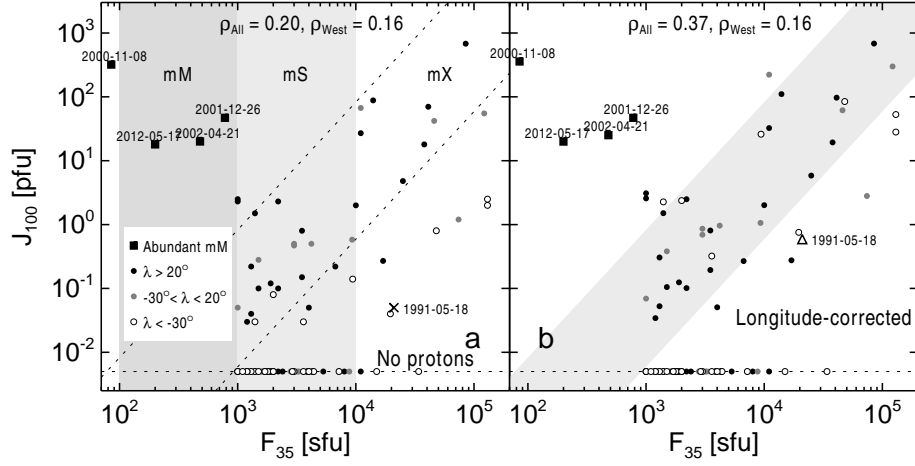


Figure 1. Peak fluxes of > 100 MeV protons versus peak microwave fluxes at 35 GHz: (a) actual values, (b) with a positional correction. The longitude of the solar source for each data point is coded by the symbols explained in the legend in panel (a). The filled squares denote the mM events with atypically high SPEs. The 64 events without detectable proton fluxes falling outside the plot region are schematically presented at the horizontal dotted line below. The Pearson correlation coefficients specified in each panel were calculated separately for all 44 proton events (ρ_{All}) and for 26 West proton events only (ρ_{West}). The slanted dotted lines, $(F_{35}/13000)^2$ and $(F_{35}/1100)^2$, in panel (a) and the corresponding shading in panel (b) enclose the majority of data points ('main sequence'), indicating a direct relation between the observed F_{35} and J_{100} . (Adapted from Grechnev *et al.*, 2013b).

handle this event, as if it had a middle east longitude of E45. The corresponding triangle in Figure 1b shows that this correction is not excessive.

All of the calculated correlation coefficients and regression parameters refer to logarithms of analyzed quantities rather than actual values because of their wide ranges. This way of linearization allows one to use linear correlation analysis widely applied in many studies mentioned. On the other hand, logarithms of zero values are infinite that requires a separate analysis of such terms. In addition, applying linear statistical methods to logarithms inevitably results in biased estimates due to the strong nonlinearity. Thus, the usage of the logarithmic scale is a necessary compromise, which allows comparing and quantifying statistical trends of an analyzed quantity on various parameters, but it is not mathematically rigorous.

2.2. Peak Flux at 35 GHz and the Probability of a High-Energy SPE

The percentage of SPEs associated with mX bursts is 90%. Protons > 100 MeV were observed in 85% of the mX events. GLEs occurred after 30% of the mX events; besides the mX events, GLEs only occurred after two abundant mM events and two far-side mO events. The probability of a proton enhancement after an mS burst is considerably lower, 52% for $E_p > 10$ MeV and 35% for $E_p > 100$ MeV. None of the mS events produced a GLE.

It is difficult to evaluate the probability of SPEs after mM bursts because of their large number (270) and insufficient accuracy of the software, which

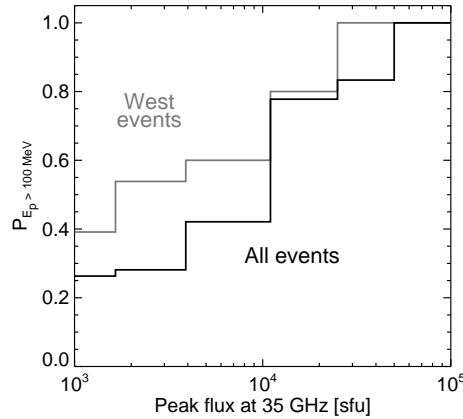


Figure 2. Probability of a near-Earth proton enhancement with $E_P > 100$ MeV *vs.* peak flux of the 35 GHz burst irrespective of the burst duration or the position of a solar source.

calculates the parameters of the bursts posted at the NoRP Web site. An accurate processing about 600 events is needed for a correct evaluation of the probability. Instead of this, we roughly estimate the upper and lower boundaries for the probability, using these lists and a catalog of SPEs presented at <http://umbra.nascom.nasa.gov/SEP/>. The total number of proton events with $J_{10} > 10$ pfu in the catalog from 1990 to March 2015, whose solar sources fell into the observing time in Nobeyama or were uncertain, was 70. Protons > 100 MeV were not observed in all of these events. Proceeding from the number of events in the catalogs, the probability of > 10 MeV SPEs after mM bursts was estimated to be within (8–23)%. The probability of high-energy SPEs after mM bursts was somewhat lower.

Figure 2 presents a more detailed probability distribution of high-energy SPEs depending on the 35 GHz peak flux, F_{35} . The shape of the histogram is sensitive to the bins because of a relatively small number of events. The intervals were chosen to reach a possibly larger number of bins, keeping the histogram monotonic. After a microwave burst with a peak flux of $F_{35} \approx 10^3$ sfu, the SPE probability is 25–40%. With an increase of F_{35} , the probability increases, approaching 100% for $F_{35} > 5 \times 10^4$ sfu. The SPE probability after a west solar event is 10–20% higher than the probability averaged over the whole set of events.

Thus, the probability of a proton enhancement directly depends on the peak flux of the microwave burst at 35 GHz. This fact is consistent with a result of Dierckxsens *et al.* (2015) and the conclusion of Grechnev *et al.* (2013b) that a powerful microwave burst indicates at a large proton event with a hard spectrum, up to a GLE, if the duration of the burst is long. The last condition is analyzed in the next section.

2.3. The Role of Duration of Microwave Burst

The distribution of SPE peak fluxes *vs.* the peak fluxes of the microwave bursts and their durations obtained by Grechnev *et al.* (2013b) confirmed the well-

known reduced proton productivity of short-duration events. However, this distribution does not resemble two separate clusters with different durations that could be expected as a manifestation of two different acceleration mechanisms. Instead, a general, although scattered, tendency is surmised. To find the reasons for the reduced proton productivity of impulsive events, we firstly consider the properties of the distribution of microwave bursts on their duration, and in the next section we analyze the correlations between various combinations of the peak values and fluences of microwave bursts and proton enhancements.

The events without detectable proton fluxes are presented at the horizontal dotted line at the bottom of Figure 1. The half-height durations of the corresponding microwave bursts range from 0.3 to 62 min with an average of 7.7 min ($\sigma_n = 10.2$ min). The durations of SPE-related events range from 2 to 80 min with an average of 14.1 min ($\sigma_p = 16.5$ min). The difference in the durations by a factor of 1.8 appears only in averages, and its significance is questionable.

Let us consider the properties of the distributions of microwave bursts with $F_{35} \geq 10^3$ sfu on their durations for SPE-related and non-SPE-related events separately irrespective of their other parameters. The histograms of these distributions calculated in a straightforward way are inconclusive because of the relatively small number of events. We have used for the analysis a different way of calculating the integral probability distribution, $P(\Delta t \leq t)$. It is an antiderivative of the histogram with a maximum normalized to unity and characterizes the probability of an event, if its duration Δt does not exceed a value of t .

The solid histogram-like line in Figure 3a presents the integral probability distribution for SPE-related microwave bursts depending on their duration. This distribution in the linear and logarithmic representations seems to be close to the error function, $\text{erf}(t/\tau)$, indicating that the duration distribution is close to normal. The derivative of the integral distribution $P(\Delta t \leq t) = \text{erf}(t/\tau)$ is a probability density function, which is known to be a Gaussian centered at zero, $2 \exp\{-(t/\tau)^2\}/(\tau\sqrt{\pi})$. By minimizing the difference between the actual distribution and the fit, we have found $\tau_p = 18.3$ min, which characterizes a typical duration of a SPE-related microwave burst. The corresponding fitting functions are shown by the dotted lines in Figures 3a and 3b.

The character of the duration distribution for non-SPE-related events turned out to be the same (Gaussian centered at zero), but with a lesser width, $\tau_n = 9.9$ min (Figures 3c and 3d). The fit is shown by the dashed line. For comparison, the gray dotted line in Figure 3d is the fit of the distribution for proton events. The ratio of the widths of the distributions for proton and non-proton events, $\tau_p/\tau_n = 1.8$, corresponds to the ratio of their actual average durations.

A calculated ratio of the probabilities of proton and non-proton events in Figure 3d is $P_p/P_n = \tau_p/\tau_n \exp\{t_{35}^2(1/\tau_p^2 - 1/\tau_n^2)\}$. If the duration of a microwave burst, t_{35} , is known, then the probability of a proton enhancement, $P_p(t_{35})$, can be estimated as

$$P_p(t_{35}) = 1/(P_p/P_n + 1) = (\tau_p/\tau_n \exp\{t_{35}^2(1/\tau_p^2 - 1/\tau_n^2)\} + 1)^{-1}. \quad (1)$$

With the parameters found for the analyzed set of events, this equation gives an estimate of 52%. Actually, SPEs occurred after 41 out of 103 microwave bursts

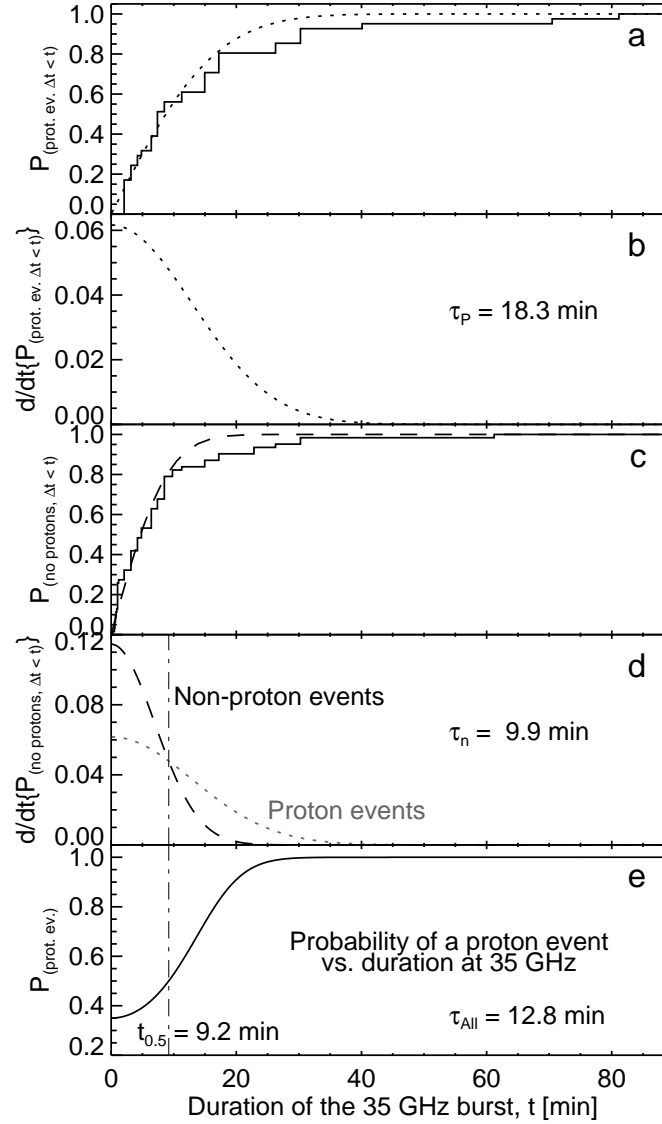


Figure 3. Probability distributions of microwave bursts with peak fluxes $F_{35} \geq 10^3$ sfu on their durations. (a) Integral and (b) differential probability distributions for SPE-related events; (c) and (d) same for non-SPE-related events; (e) probability of a proton enhancement depending on the duration of the microwave burst. The histogram-style lines represent actual distributions, and the dotted curve show the analytic fit. The gray dotted curve in panel (d) corresponds to the analytic fit in panel (b). The vertical dash-dotted line in panels (d) and (e) corresponds to the 50% probability ($t_{35} = 9.2$ minutes).

with fluxes $F_{35} \geq 10^3$ sfu, *i.e.*, in $\approx 40\%$ of the events. The calculated probability for proton events *vs.* the duration of the 35 GHz burst is shown in Figure 3e. The vertical dash-dotted line in Figures 3d and 3e denotes the burst duration of $t_{0.5} = 9.2$ min, at which the distribution functions of the proton and non-proton events are equal, that corresponds to the probability of 0.5. According to Figure 3e, if the peak flux of the 35 GHz burst exceeds 10^3 sfu and its duration exceeds 30 min, then the SPE probability is close to 100%.

The identity of the distribution functions for SPE-related and non-SPE-related events indicate the absence of essential differences between these classes of the events manifesting in their durations. The duration distribution of the whole set of microwave bursts, including both proton and non-proton events, is also close to the normal distribution with $\tau_{\text{All}} = 12.8$ min. This distribution is not associated in any way with the proton productivity of the events, being an intrinsic characteristic of microwave bursts. A probable reason for the different widths of the distributions, $\tau_n < \tau_{\text{All}} < \tau_p$, is the sensitivity of the detectors, which measure the proton fluxes in the Earth orbit against the radiation background. The decrease of the SPE peak due to the velocity dispersion of the proton bunch in the interplanetary space and other propagation effects is particularly strong, if the bunch has a short duration.

The velocity dispersion (SPE rise) time for > 100 MeV protons can be roughly estimated as a difference between the straight Sun–Earth propagation times of the 100 MeV and relativistic protons, $t_D \approx 1 \text{ AU} \times (1/v - 1/c) = 1 \text{ AU}/c \times (1/\sqrt{1 - 1/(E/m_p + 1)^2} - 1) \approx 11$ min, with $E = 100$ MeV, v , and m_p being the kinetic energy, velocity, and the rest mass of protons; c is the speed of light. A high-energy rollover of the proton spectrum decreases t_D , while the actual path length, including the Parker spiral and particularities of the propagation in the interplanetary space, increases t_D . Thus, $t_D \sim t_n$, consistent with our assumption. Similar reasons might also control the dependence of the SPE probability on the peak of the microwave burst shown in Figure 2.

The absence of two different clusters in the durations of the events, the absence of characteristic durations of the 35 GHz bursts in the events with protons and without them, and, instead, the same shapes of their distributions with most probable zero durations are not consistent with the two distinct classes of ‘impulsive’ and ‘gradual’ events. Therefore, a possible reason for the dependence of the number of high-energy protons on the duration of the event can be not a difference in the particle acceleration mechanisms, but the duration of the acceleration process, on which the proton fluence should be directly dependent in any case. It seems also reasonable to consider the microwave fluence in addition to the peak flux. The fluence is an energy characteristic of the microwave emission throughout the flare, while the peak flux characterizes the maximum of its power spectral density observed in the event. The correlations between various combinations of peak values and fluences of the microwave bursts and proton enhancements are analyzed in the next section.

2.4. Microwave and Proton Fluences

The relations between various combinations of the peak fluxes and fluences of microwave bursts and proton enhancements are presented in Figure 4. The cor-

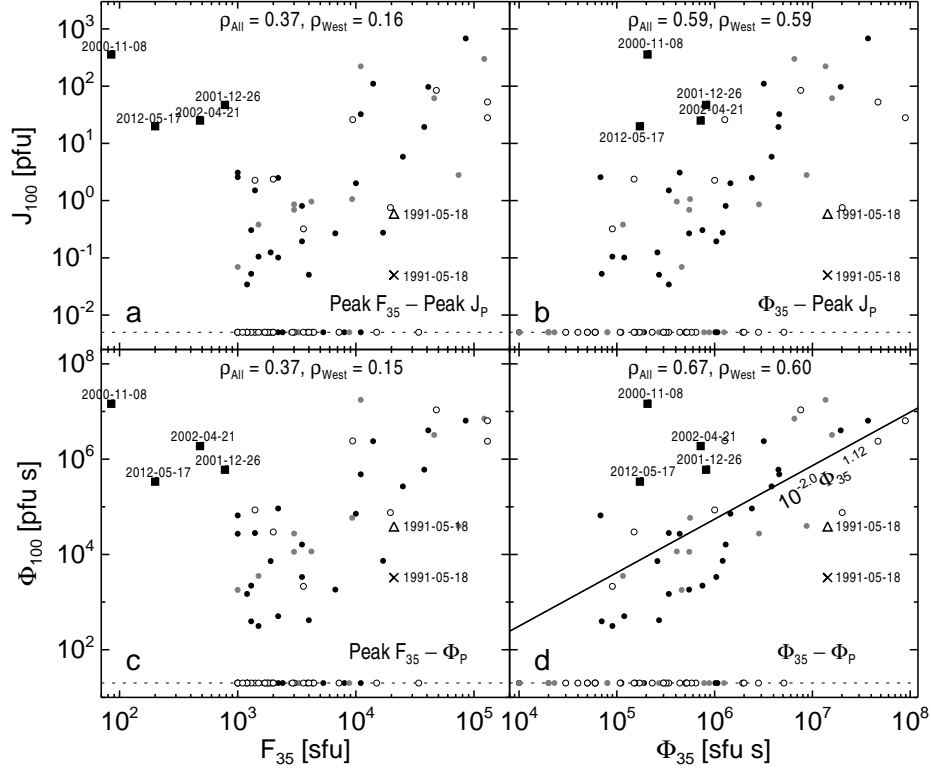


Figure 4. Statistical relations between different combinations of the peak fluxes and fluences of microwave bursts, on the one hand, and those of longitude-corrected SPEs, on the other hand. The Pearson correlation coefficients specified in each panel were calculated separately for all 44 SPEs presented (ρ_{All}) and for 26 West events only (ρ_{West}). The meaning of the symbols is the same as in Figure 1. The line in panel (d) represents the linear fit of the (log-log) distribution. The poorly connected 18 May 1991 event is shown both with a correction (triangle) and without it (slanted cross).

relation coefficients for all events and, separately, for west events only are shown in the upper parts of the plots. The poorly connected event 5 was treated with a correction described in Section 2.1. This increased the correlation coefficients only insignificantly (*e.g.*, ρ_{All} from 0.64 to 0.67 in Figure 4d).

The scatter of the data points in the top and bottom left panels is similar. The four abundant events deviate from the main cloud of points considerably less in the right panels, where the argument is Φ_{35} , than in the left panels, where the argument is F_{35} . The main cloud of points without the four abundant events is narrower in Figure 4d than in Figure 4b. The best correspondence between the proton and microwave fluences is confirmed by the highest correlation coefficient of 0.67 for this combination of the parameters. Note that Kahler (1982) found the microwave fluences to correlate with peak proton fluxes higher than the BFS hypothesis predicted (which corresponds to our Figure 4b), but he did not consider the relation between the microwave and proton fluences (Figure 4d).

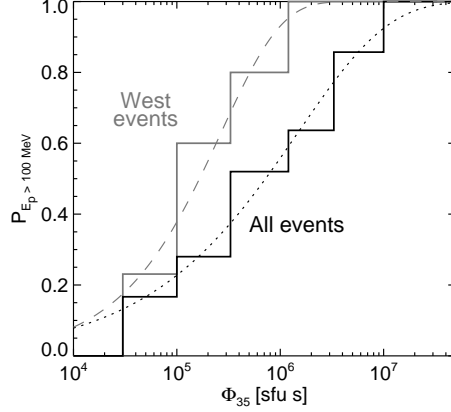


Figure 5. Probability of a near-Earth proton enhancement with $E_p > 100$ MeV *vs.* the microwave fluence at 35 GHz irrespective of any other parameters.

Extraordinarily high fluxes of high-energy protons were observed in four abundant mM events selected by our criteria. It is possible that these events were essentially different from the others. As Figure 4 shows, the highest correlation between the microwave and proton fluences can be due to the long duration of the abundant events. However, even for the whole set of events with $F_{35} > 1000$ sfu without the abundant events, the correlation coefficient between the fluences is 0.82, and does not exceed 0.75 for other combinations. Thus, the correlation between the microwave and proton fluences is highest in any case.

The linear fit for the whole data set is $\Phi_p = 10^{-1.99 \pm 1.18} \Phi_{35}^{1.12 \pm 0.19}$, and the correlation coefficients are $\rho_{\text{All}} = 0.67$, $\rho_{\text{West}} = 0.60$. The data set without the abundant mM events and atypical event 5 is fit with $\Phi_p = 10^{-4.17 \pm 0.96} \Phi_{35}^{1.44 \pm 0.15}$, and the correlation coefficients are $\rho_{\text{All}} = 0.84$, $\rho_{\text{West}} = 0.91$. The nonlinearity of the relation might be due to the complex dependence of the gyrosynchrotron emission on the parameters of radiating electrons, including their spectral and spatial distributions, magnetic field strength, and other factors (Dulk and Marsh, 1982; Kundu *et al.*, 2009). Our choice of a high frequency of 35 GHz simplifies the situation; the scatter at a lower frequency can be wider due to the influence of these factors.

Because the probability of a detectable > 100 MeV SPE depends directly on the peak flux and duration of a 35 GHz burst (Figure 2 and Equation 1), its relation with the 35 GHz fluence in Figure 3 is pronounced still clearer in the histograms with nearly equal bins covering a range of three orders of magnitude. The distributions can be approximately fitted by the empirical relations

$$\begin{aligned} P_{\text{All}}(\text{SPE}, E_p > 100 \text{ MeV}) &\approx 1 - \exp\{-[\Phi_{35}/(1.5 \times 10^6)]^{0.5}\} \\ P_{\text{West}}(\text{SPE}, E_p > 100 \text{ MeV}) &\approx 1 - \exp\{-[\Phi_{35}/(2.7 \times 10^5)]^{0.75}\}. \end{aligned} \quad (2)$$

In future, when calibrated microwave measurements would be available in real time, such relations could be used to promptly forecast the probability and importance of nearing SPEs with ongoing update of the quantities issued.

3. Origin of High-Energy SPEs

The direct relation between the microwave and proton fluences indicates the dependence of the total number of high-energy protons arriving at the Earth orbit on the total duration of the acceleration process. The correspondence between the durations of the acceleration process and the microwave burst is obvious, but it is more difficult to expect such a correspondence, if the protons are accelerated by shock waves far away from a flare region. Thus, the results of the preceding Section 2.4 favor predominantly flare-related origin of the analyzed SPEs ($F_{35} \geq 10^3$ sfu) with respect to the hypothesis of their exceptional shock-acceleration. A contribution from shock-acceleration is also possible, but with a lesser statistical significance — probably, in the abundant events. The suggestion is consistent with the preliminary conclusion of Trottet *et al.* (2015) deduced from a different approach. The authors analyzed correlations between peak proton fluxes and parameters of flares and CMEs. To additionally verify our statistical conclusions, we will apply their approach to our data set.

3.1. Relations Between Parameters of Eruptive Solar Activity and Proton Fluences

Trottet *et al.* (2015) analyzed 44 SPEs in an energy range of 15–40 MeV (and corresponding fluxes of subrelativistic electrons) associated with flares of M and X GOES classes that occurred in 1997–2006 in the west solar hemisphere. The authors calculated correlation coefficients between logarithms of peak proton fluxes and parameters characterizing the flares and CMEs. The analyzed parameters were the peak flux of the SXR emission, start-to-peak SXR fluence, microwave fluence, and CME speed.

In the proton energy range of 15–40 MeV analyzed by Trottet *et al.* (2015), it is difficult to filter out the contribution from the acceleration by interplanetary shock waves far away from the Sun that is, most likely, considerably less for proton energies above 100 MeV. As Figure 4 and the related text show, the microwave fluence, Φ_{35} , correlates with total proton fluence, Φ_{SXR} , considerably better than with the peak proton flux, J_p . Therefore, we analyze the correlations with total fluences of SPEs rather than their peak fluxes.

Systematic information about CMEs and their plane-of-the-sky speeds is available in the CME catalog for events since 1996 (Yashiro, 2004; http://cdaw.gsfc.nasa.gov/CME_list/). The speeds listed in the CME catalog are measured for the fastest feature, and therefore V_{CME} for fast CMEs are most likely related to shock waves (see, *e.g.*, Ciaravella, Raymond, and Kahler, 2006). The halo shock fronts ahead of expanding fast CMEs should have the shapes close to spheroidal or elliptical ones (Grechnev *et al.*, 2011, 2013a, 2014; Kwon, Zhang, and Olmedo, 2014; Kwon, Zhang, and Vourlidas, 2015), and therefore the plane-of-the-sky speeds measured in the catalog should not be drastically different from the modules of their vectors. The CME speeds are known for 28 proton events listed in Table 1.

Figure 6 shows the logarithmic scatter plots of the proton fluence above 100 MeV with the longitudinal correction, Φ_{100} , *vs.* total microwave fluence, Φ_{35} (Figure 6a); SXR peak flux, I_{SXR} (Figure 6b); its start-to-peak SXR fluence,

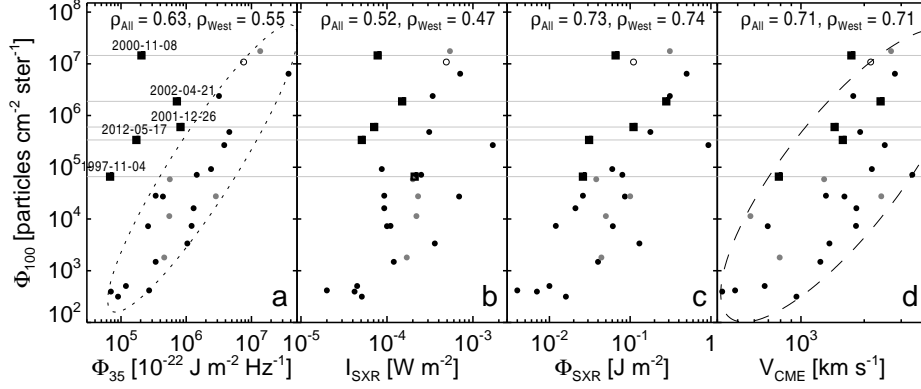


Figure 6. Scatter (log-log) plots of longitude-corrected SPE fluence, Φ_{100} , versus microwave fluence, Φ_{35} , peak SXR flux, I_{SXR} , start-to-peak SXR fluence, Φ_{SXR} , and CME speed, V_{CME} . The Pearson correlation coefficients specified in each panel were calculated separately for all 28 events presented (ρ_{All}) and for 22 West events only (ρ_{West}). The meaning of the symbols is the same as in Figure 1. The gray horizontal lines trace the fluences in the abundant events. The broken ellipses in panels (a) and (d) enclose all but abundant events.

Φ_{SXR} (Figure 6c); and the CME speed, V_{CME} (Figure 6d). The events without SPEs, whose logarithms are infinite, are not included in the correlation analysis. These events presented in Figure 5 should be handled using Equation (3).

The results are close to those of Trottet *et al.* (2015). All of the scatter plots show a similar direct tendency with a scatter of the same order. Correlations in Figure 6a and 6b are considerably lower for 22 west events with $\lambda > 20^\circ$ than for all events because of a large contribution from the four west abundant mM events. The higher correlation of the proton fluence, Φ_{100} , with SXR fluence, Φ_{SXR} , than with the peak SXR flux, I_{SXR} , is consistent with the significance of both the intensity and duration of the acceleration process. On the other hand, the contribution from the BFS is not excluded.

Figure 6a additionally indicates that the 4 November 1997 event (SOL1997-11-04T05:58, 51 in Table 1) probably belongs to the abundant events, too. This event was associated with a short-duration (3 min) microwave burst up to 1000 sfu and a relatively slow CME (785 km s^{-1}), but its proton fluence was atypically high relative to the events with comparable microwave fluences. In its SXR peak flux of X2.1, this event is not atypical. By its SXR fluence and the CME speed, this event resides in the upper part of the main cloud of points.

It is reasonable to assume that in the proton-abundant events, depending on their location relative to the main cloud of points in Figure 6, the contribution of shock-accelerated protons dominated. It is also possible that some additional factors were implicated, especially for the event 2000-11-08, which stands apart in Figure 6d by its abundant proton fluence, while the CME speed of 1738 km s^{-1} is insufficient to fit within the cloud of points.

Now we consider the remaining events, excluding the abundant mM events. For convenience we have plotted in Figures 6a and 6d the ellipses enclosing all of the non-abundant events. The ellipticity is known to visually characterize the correlation coefficient. The points inside the dotted ellipse in Figure 6a are

obviously least scattered with respect to the parameters of the SXR emission and CME speed in other panels. Thus, the BFS measure referring to the SXR emission used by Kahler (1982) cannot account for the high correlation between the microwave and proton fluences. This close correlation persists over three orders of magnitude for Φ_{35} and five orders of magnitude for Φ_{100} . It would be surprising to have this conspicuous correspondence as an insignificant secondary effect due to BFS.

The dashed ellipse in Figure 6d characterizes the importance of the shock-acceleration according to Trottet *et al.* (2015). While almost all of the abundant events fall within the ellipse, the scatter here is obviously larger than in Figure 6a. The close correlation between Φ_{35} and Φ_{100} cannot be a result of the scattered correlation between V_{CME} and Φ_{100} due to the interdependence of the analyzed parameters. Thus, it cannot be caused by the BFS. For reliability, statistical characteristics of these relations are examined quantitatively in the next section.

The range of the CME speeds is one order of magnitude, being limited from below by about 400 km s^{-1} , suggesting a lower limit required for CME to drive a bow shock. On the other hand, CMEs spend large energy to overcome gravity (Uralov, Grechnev, and Hudson, 2005). The gravity escape velocity at the inner boundary of the LASCO/C2 field of view, $r_{(\text{C}2)} = 2R_{\odot}$, is $\sqrt{2GM_{\odot}/r_{(\text{C}2)}} \approx 440 \text{ km s}^{-1}$ (G the gravity constant, R_{\odot} and M_{\odot} the radius and mass of the Sun). Slower CMEs, whose propelling forces cease at lesser heights (mainly from small sources), would not stretch closed structures enough to enable efficient escape of trapped flare-accelerated particles, or even fall back without any appearance in the LASCO/C2 field of view. The majority of the escaping slower CMEs is probably due to eruptions of large quiescent filaments gradually accelerating up to large distances. SPEs are not expected from such CMEs, which are too slow to produce shock waves and are non-flare-related. The lower limit for the speeds of SPE-related CMEs of about 400 km s^{-1} is expected in any case.

3.2. Analysis of the Correlations

To exclude secondary correlations between parameters, which are not related physically, we use partial correlation coefficients, following the approach of Trottet *et al.* (2015). Unlike the classical Pearson correlation coefficients, the partial correlation coefficients reveal the own contribution from each of the parameters, suppressing the interdependence between them. The partial correlation coefficient, $\rho_j(x_j, y)$, between the analyzed parameter, x_j , and the dependent random variable, y , is calculated as the usual Pearson correlation coefficient between x_j and the difference $(y - Y_j)$, where Y_j is the best linear fit of y , calculated from other parameters. The linear regression is used as the best fit Y_j :

$$Y_j = C + \sum_{i \neq j} x_i.$$

The partial correlation coefficient can be considerably less than the Pearson coefficient, but cannot exceed it.

Table 2. Correlations between parameters of the solar eruptive activity and SPE fluences in 28 events (1996–2014) in comparison with results of Trottet *et al.* (2015)

Correlation coefficients (1)	All events (28)		$\log_{10} \Phi_{100}$ Without abundant events (23)		$\log_{10} J_{15}$ Results of Trottet <i>et al.</i> (2015) (6)
	Actual (2)	Corrected (3)	Actual (4)	Corrected (5)	
Pearson cor. coef.					
$\log_{10} \Phi_{35}$	0.58	0.63	0.89	0.90	0.67
$\log_{10} I_{\text{SXR}}$	0.47	0.52	0.73	0.74	0.54
$\log_{10} \Phi_{\text{SXR}}$	0.73	0.73	0.82	0.79	0.76
$\log_{10} V_{\text{CME}}$	0.71	0.71	0.77	0.75	0.67
Partial cor. coef.					
$\log_{10} \Phi_{35}$	−0.02	0.09	0.59	0.67	−0.10
$\log_{10} I_{\text{SXR}}$	−0.37	−0.25	−0.16	0.09	0.06
$\log_{10} \Phi_{\text{SXR}}$	0.57	0.47	0.36	0.10	0.42
$\log_{10} V_{\text{CME}}$	0.39	0.33	0.14	0.001	0.36
	Without account of V_{CME}				
$\log_{10} \Phi_{35}$	0.18	0.27	0.70	0.74	
$\log_{10} I_{\text{SXR}}$	−0.38	−0.27	−0.14	0.10	
$\log_{10} \Phi_{\text{SXR}}$	0.64	0.55	0.35	0.10	

Table 2 presents the Pearson and partial correlation coefficients between the analyzed parameters for all 28 events (columns 2 and 3) and for 23 events, excluding the abundant mM events (columns 4 and 5). The correlation coefficients were calculated for both the actual proton fluences (columns 2 and 4) and for the longitude-corrected ones (columns 3 and 5). The Pearson correlation coefficients in the four upper rows of column (3) correspond to Figure 6. For comparison, column (6) lists the results obtained by Trottet *et al.* (2015) for peak proton fluxes, J_{15} , of a lower energy range of 15–40 MeV.

As Trottet *et al.* (2015) analyzed only the west events (without a longitude correction), to which both flare-related and shock-related contributions were possible, their results in column (6) should be compared with column (3). The Pearson correlation coefficients in these columns are close to each other. The partial correlation coefficients in columns (3) and (6) for Φ_{35} and I_{SXR} are more distinct, while the overall conclusion of Trottet *et al.* (2015) is confirmed. The correlations between the SPEs and either the total microwave fluences or the SXR peak fluxes for all 28 events are insignificant. The correlations of high-energy proton fluences with the start-to-peak SXR fluences and the CME speeds are significant. The partial correlation coefficients of Φ_{100} with Φ_{SXR} and with V_{CME} are close to each other. Thus, our results for 28 events agree with those of Trottet *et al.* (2015).

Columns (4) and (5) present the results for the same set of events, except for the five abundant events. The Pearson correlation coefficients between the proton fluences and all independent parameters considerably increase, depending

on the longitude correction weakly. The partial correlation coefficients increase sharply for Φ_{35} and considerably reduce for V_{CME} . The influence of the longitude correction is strong here. The dependence on the SXR emission becomes weak, probably due to an indirect correlation via Φ_{35} . These circumstances apparently confirm the predominant flare origin of high-energy protons in the 23 events (columns 4 and 5), and the major contribution from the shock-acceleration in the five abundant events. The longitudinal correction sharply decreases the significance of Φ_{SXR} , probably, due to its interdependence with Φ_{35} .

We are not aware of the CME speeds for 15 proton events of 1990–1992 and event 54 (1998-11-22). Therefore, a rigorous analysis of the partial correlation coefficients with all of the analyzed parameters for the complete set of the 40 SPEs from 1990 to 2015 is not possible. We will try to approximately estimate the significance of the contributions from different sources by calculating the partial correlation coefficients with no account of V_{CME} for the considered sets of 28 and 23 events. They are shown in the bottom three rows of Table 2. Then we compare these values with similar results obtained for all 40 events.

The partial correlation coefficients with I_{SXR} in all columns and with Φ_{SXR} in columns (4) and (5) are almost insensitive to the absence of V_{CME} . The largest increase show the partial correlation coefficients with Φ_{35} in columns (2) and (3), possibly due to their interdependence with V_{CME} . Their increase is not as large in the columns (4) and (5), where the influence of V_{CME} is less.

The correlation coefficients for all 40 SPEs from our list, excluding the five abundant events, are listed in Table 3. The Pearson correlation coefficients between the proton fluences and the other known parameters are not much different from the values in columns (4) and (5) of Table 2. The partial correlation coefficients with Φ_{35} slightly decrease, remaining the largest ones. Similar to column (5), Φ_{SXR} turns out to be insignificant, while the importance of I_{SXR} sharply increases. This fact is not surprising, because, firstly, Φ_{35} is related to the total flare energy, while I_{SXR} is associated with its maximum power. Both parameters can be important. Secondly, an indirect correlation between the proton fluence and I_{SXR} through the unknown V_{CME} is possible. The microwave fluence is most significant anyway.

The results lead to the following conclusions. i) The quantitative analysis of the correlation coefficients confirms the conclusions of the preceding Section 3.1. ii) The partial correlation coefficients are sensitive to the analyzed set of events and allow one identifying significant parameters, but do not guarantee independence of other parameters. iii) The predominance of the flare contribution to high-energy proton enhancements in the 40 events of 1990–2015 with $F_{35} \geq 10^3$ sfu seems to be undoubted, while the contribution from shock-acceleration is not excluded in these events. iv) Similarly, the predominance of the shock-acceleration in the five abundant events seems to be certain, while the flare contribution in these events is not excluded, too.

In summary, the quantitative analysis confirms the apparent outcome from Figures 4d and 6d. The statistical predominance of the flare-related contribution to SPEs after the bursts with $F_{35} \geq 10^3$ sfu observed during 25 years by NoRP is confirmed by the scatter plot in Figure 4d. It does not reveal conspicuous outliers, except for the five presumably shock-dominated abundant events. Some

Table 3. Correlations between parameters of flares and SPE fluences in 40 presumably flare-dominated events (1990–2014)

	$\log_{10} \Phi_{100}$	
	Actual	Corrected
Pearson correlation coefficients		
$\log_{10} \Phi_{35}$	0.77	0.82
$\log_{10} I_{\text{SXR}}$	0.66	0.75
$\log_{10} \Phi_{\text{SXR}}$	0.66	0.74
Partial correlation coefficients		
$\log_{10} \Phi_{35}$	0.56	0.62
$\log_{10} I_{\text{SXR}}$	0.33	0.46
$\log_{10} \Phi_{\text{SXR}}$	−0.16	−0.15

of them in the $V_{\text{CME}} - \Phi_{100}$ scatter plot (Figure 6d) surpass in proton fluences their neighbors in the cloud of the points. This circumstance indicates a possible implication of some factors amplifying their proton productivity.

4. Discussion and Conclusion

4.1. Results of the Analysis

The dependence of the probability of a proton enhancement on the duration of the microwave burst was analyzed, its empirical quantitative description was proposed. Unlike the traditional estimate of the flare duration from its SXR emission, we used the duration of the microwave burst at 35 GHz, Δt_{35} . According to the Neupert effect (Neupert, 1968), Δt_{35} should be close to the duration of the rise phase in SXR. Therefore, the difference between our estimates and the traditional way should not be large.

Clustering the events according to the durations of the 35 GHz bursts, expected for the categories of ‘impulsive’ and ‘gradual’ events, was not revealed for the proton enhancements of > 100 MeV. This result might be due to a usual displacement of the microwave turnover frequency below late in long-duration events, decreasing the flux density at 35 GHz. Considerable efforts were applied previously to search for a criterion or index of the flare ‘impulsiveness’ (*e.g.*, Cliver *et al.*, 1989), but no certain quantitative result was obtained. Two presumable categories, differing in their particle composition and other properties, were distinguished in their durations only qualitatively. To clarify the situation, we analyzed the correlations between all combinations of the peak fluxes and fluences for the proton enhancements and the microwave bursts. For the majority of the analyzed events, the highest correlation was found between the proton fluences, on the one hand, and the microwave and SXR fluences, on the other hand (Figure 6). In other words, the total number of near-Earth protons is controlled by both the intensity of the particle acceleration process and its

duration. This circumstance points at a correspondence between the durations of the proton acceleration process and the flare that is obvious for the flare origin of protons, but more difficult to understand for the proton acceleration by shock waves. Thus, a probable reason for the dependence of the number of high-energy protons on the duration of an event is not a difference between the particle acceleration mechanisms, but the duration of the acceleration process.

Some conceptions of the properties of the two different categories of ‘impulsive’ and ‘gradual’ events might be probably due to the traditional idea that impulsive events are associated with confined flares and long-duration events (LDEs) are associated with eruptive flares. However, two decades of SOHO/LASCO observations have shown that this assumption was oversimplified. Indeed, most confined flares are short, and most LDEs are associated with CMEs. However, many impulsive flares are obviously eruptive, *e.g.*, events 19, 51, 55, 56, 58, 66–69, 90, 93, and 94 in Table 1. They include GOES X-class flares and halo CMEs. On the other hand, confined LDE flares are known, *e.g.*, some of the events in active region 12192 in October 2014 (Thalmann *et al.*, 2015; also, *e.g.*, event 101 in Table 1). These circumstances indicate that the duration of an event is not a reliable indicator of a dominating acceleration mechanism. In particular, one of the five presumably shock-dominated abundant events (51 in Table 1) was an impulsive one.

Recently, Reames, Cliver, and Kahler (2014) analyzed the SEP composition of 111 impulsive events with a high iron abundance and concluded that the sources of their major part were associated with CMEs. It is interesting to analyze a possible overlap of the events from their list with the NoRP data which we considered. We found that the sources of 39 events from that list fell within the NoRP observation time. Four events are present in our Table 1 (56, 59, 64 and 93); weak proton enhancements above 100 MeV were observed after three of them. One major proton event (2004-11-01, 05:50) was probably due to a behind-the-limb source. The peak fluxes at 35 GHz did not exceed 100 sfu in 19 events. No bursts at 35 GHz were detectable in 16 events. Most of these events did not produce noticeable proton enhancements even in the > 10 MeV range.

In this respect, a direct dependence of the probability of proton enhancements on the peak intensity of microwave bursts at 35 GHz seems to deserve attention. It is important for diagnostic purposes. Possibly, such a dependence can be manifest at frequencies below 35 GHz, for which round-the-clock observations are more representative. The only event from the analyzed set, with a 35 GHz peak flux of 10^3 sfu, was probably shock-dominated. These facts suggest a possible indication at a dominating flare-related source of high-energy SPE, if $F_{35} > 10^3$ sfu, or a prevailing shock-related source, if $F_{35} < 10^3$ sfu.

4.2. Are the Two Alternative Concepts Really Incompatible?

As mentioned, the statistical domination of flare-related acceleration of high-energy proton enhancements in most of the events, which we analyzed, does not exclude a contribution from shock-related acceleration in these events. It is supported, for example, by the analyses of the SEP composition (*e.g.*, Reames,

2009, 2013, and many others). Recent observational studies (Qiu *et al.*, 2007, Temmer *et al.*, 2010, Grechnev *et al.* 2011, 2013a) have revealed a closer association between solar eruptions, flares, shock waves and CMEs, than previously assumed. The shock waves initially appear early in the low corona, during the rise phase of a hard X-ray and microwave burst. Particle acceleration by flare processes and shock waves can occur nearly concurrently, and therefore it is hardly possible to recognize their origin from the analysis of temporal relations or velocity dispersion. On the other hand, the account of the early appearance of shock waves at low altitudes can be helpful in the studies of the SEP acceleration by shock waves.

Conclusions about the origin of near-Earth proton enhancements made on the basis of oversimplified old hypotheses without confronting with recent observations might be inadequate. Taking into account the results of our analysis and those of Trottet *et al.* (2015), one can expect that shock-acceleration is responsible for the bulk of protons and ions accelerated to low to moderate energies. On the other hand, the major role of shock waves in the acceleration of GLE particles, which represent the SPE category with a hardest spectrum, looks questionable in events associated with power flares. Indeed, apparently shock-dominated non-flare-related SPEs are characterized by soft spectra (see, *e.g.*, Chertok, Grechnev, and Meshalkina, 2009; Gopalswamy *et al.*, 2015). The hardness of the proton spectra in GLE-related events is confirmed by our data set. All of such events (marked with a superscript ‘¹’ in column (13) of Table 1) had proton indices $\delta_p < 1.5$. Protons with energies above 100 MeV are sometimes observed in non-flare-related SPEs, but their percentage is less than in flare-related events. For example, a detailed analysis of the origin of SPE in the extreme 20 January 2005 event responsible for GLE69 led Grechnev *et al.* (2008) and Klein *et al.* (2014) to the conclusions about the flare source of SPEs. Similarly, the analysis by Grechnev *et al.* (2013a) of the 13 December 2006 event responsible for GLE70 revealed inconsistency of previous arguments in favor of its exceptional shock-related source. It is possible that in exceptional non-flare-related events shock-accelerated proton fluxes are sufficient to produce a GLE under favorable conditions (Cliver, 2006). However, it is difficult to expect that if a powerful flare occurs, then shock-accelerated protons provide the main contribution to the GLE, relative to the flare-related contribution dominating at high energies. Note that we analyzed the GOES integral proton channel above 100 MeV, although particles of much higher energies, $\gtrsim 1$ GeV, are responsible for GLEs.

These considerations seem to be opposed by a recent study of Thakur *et al.* (2014), where the authors came to a conclusion about exceptional shock-related origin of the 6 January 2014 GLE. It was produced by a behind-the-limb SOL2014-01-06 event in active region 11936 (Table 4), where the STEREO telescopes recorded a powerful flare with an estimated GOES importance of about X2 (Chertok, Belov, and Grechnev, 2015). Proceeding from the remoteness of the flare region from the well-connected longitudes (like event 110 in Table 1 associated with GLE61 on 18 April 2001), Thakur *et al.* (2014) stated that this event, as well as other GLEs from behind-the-limb sources, posed a challenge to the flare acceleration mechanism for GLE particles. However, as the facts and

Table 4. Comparison of the proton events on 6 and 7 January 2014

Event	Position	GOES class	CME speed [km s ⁻¹]	J_{100} [pfu]	J_{10} [pfu]	δ_p
SOL2014-01-06T07:50	S15W113	\approx X2	1402	4	40	1.00
SOL2014-01-07T18:32	S11W11	X1.2	1830	4	900	2.35

speculations in the preceding paragraph show, the shock-related origin of some GLEs does not contradict the major flare contribution to the others.

Assuming a direct escape of flare-accelerated protons into the interplanetary space from the active region core in the low corona, Thakur *et al.* (2014) pointed out that the flare-accelerated particles would need to interact with the CME flux-rope to reach the well-connected field lines, and thus their scattering would not allow the high anisotropy typical of the beginning of the GLEs. It is difficult to agree with this argument, because the major cause of the anisotropy of GLE particles is their transport in the interplanetary space. There are some other complicating factors such as the perpendicular diffusion that is difficult to take into account in simple considerations. A surprising example presents an SPE caused by the 1 September 2014 event behind the east limb, when the rise phase during half a day was dominated by > 100 MeV protons. Furthermore, there is a possibility of trapping of accelerated protons in the CME flux-rope trap (similar to electrons responsible for type IV radio bursts) and their confinement until reconnection of the flux rope with an open magnetic structure such a coronal hole or streamer that allows the trapped particles access to the interplanetary space (see, *e.g.*, Masson *et al.*, 2012; Grechnev *et al.*, 2013b). In such a case, the escape conditions for protons accelerated in a flare and at the shock front ahead of a CME are practically the same.

It is useful to compare the 6 January event with another, which occurred on the next day, 7 January 2014 (Table 4), in active region 11944 on the Earth-facing solar side, and also produced an SPE, but not a GLE. The peak flux of > 100 MeV protons was the same as on 6 January, while the lower-energy SPE was stronger and longer. The 7 January CME was considerably faster than the 6 January CME. The peak flux of the gyrosynchrotron emission of 2500 sfu occurred on 7 January at about 5 GHz. All of the GLE-related events from our sample had a higher turnover frequency (Grechnev *et al.*, 2013b); parameters of the microwave emission on 6 January are unknown. The relation between the parameters of the two events is not surprising, if the softer shock-related SPE component dominating lower energies was stronger on 7 January, while the harder flare-related component dominating higher energies was stronger on 6 January. Otherwise, the relation seems to be challenging. For all of the listed reasons, the arguments against the flare-related source of the 6 January 2014 GLE are not convincing.

The existence of the two concurrent different sources of accelerated protons has been argued previously in several studies mentioned in Section 1. This alternative to the single-source hypothesis invoked by Kahler (1982) can also

be checked by comparing the peak-size distributions of SPEs and all flares. Analyzing the differential distribution functions *vs.* energy, Hudson (1978) concluded that the proton production was more efficient in more energetic flares. Three decades later, Belov (2007) have analyzed detailed distribution based on much richer data. They demonstrated that the slope of the distribution of SPE-related flares was flatter than that of all flares at their low to moderate GOES importance (*i.e.*, the SPE productivity of weaker events was less dependent on the SXR peak flux). For bigger flares, the slope of SPE-related flares approached that of all flares. These circumstances also confirm the existence of the two sources of SPEs; one, shock-related, dominates in events with weaker flares, and the second, flare-related, dominates in stronger flares. Note that the analyses of the peak-size distributions did not consider the event duration, whose role we discussed (Hudson (1978) also admitted this possibility).

All of the listed facts indicate that the role of the BFS was most likely overestimated by Kahler (1982). He stated a higher correlation between the 8.8 and 15.4 GHz fluences and SPE peak fluxes than the BFS could provide, but did not consider this correlation to be important, having not found any correspondence between the spectral parameters of SPEs and microwaves (similar conclusion was made about hard X-rays). Some aspects of this correspondence have been revealed later. Chertok, Grechnev, and Meshalkina (2009) demonstrated statistical correspondence between δ_p and spectral parameters of microwave bursts. Grechnev *et al.* (2013b) showed that the SPEs produced in events with $F_{35} > 10^3$ sfu were harder than those after weaker bursts. The results of Kahler (1982) might be determined by the limitations of the microwave data used in his analysis. Most of the 50 events he analyzed had peak microwave fluxes from 10^2 to 10^4 sfu in the whole frequency range; two only were stronger. When referred to 35 GHz, the majority of these events fall into the mM category, suggestive of prevailing shock-acceleration of SPEs, as we showed. Thus, the extension of our results to SPEs associated with weaker microwave bursts should mainly correspond to the results of Kahler (1982).

4.3. Concluding Remarks

Our analysis has not revealed a separation of the analyzed data set at 35 GHz according to their durations into the clusters of ‘impulsive’ and ‘gradual’ events. Relations have been established between the intensities and durations of microwave bursts, on the one hand, and the probability of near-Earth proton enhancements with energies > 100 MeV, on the other hand. Most likely, the causes of these dependencies are related to propagation effects of protons from their solar sources to the Earth and the limited sensitivity of the detectors. This circumstance suggests the possibility that protons are accelerated to high energies in all flares accompanied by sufficiently strong bursts at 35 GHz, *i.e.*, in all cases, when acceleration of a large number of electrons to relativistic energies occurs. This indication corresponds to the conclusions of Livshits and Belov (2004) about the simultaneous acceleration of both electrons and protons.

Our results are consistent with the main conclusion of Trotter *et al.* (2015) and confirm their suggestion about the domination of the flare acceleration

for high-energy protons. For the majority of the analyzed events, we found a direct dependence with a high correlation between the parameters of the flare and proton fluences > 100 MeV. Comparable correlations between the proton fluences with start-to-peak SXR fluences and microwave emission shows that both these parameters characterizing solar flares can be used for the diagnostics of proton enhancements, and their importance is not diminished by the Big Flare Syndrome hypothesis. Comparison of Figures 1a, 1b, 4d, and Table 3 demonstrates that finding and accounting the factors, which affect the quantitative parameters of near-Earth proton enhancements, allow one to considerably reduce the uncertainty of their expected values that is evaluated by a conspicuous increase of the correlation coefficients. Perhaps some other affecting factors exist, whose account would additionally reduce the scatter. For example, by using a combination of the peak flux, effective duration, and the turnover frequency of the microwave bursts, Isaeva, Melnikov, and Tsvetkov (2010) reached their considerably higher correlation with SPE parameters.

A detailed analysis of recent observational data promises a substantial progress in understanding the sources of near-Earth proton enhancements and their prompt forecast. It seems attractive to analyze the events, in which the contribution from only one of the two competing sources of accelerated protons is most probable. Note, however, that, according to recent observational studies, shock waves develop in the low corona during flares and the early formation of CMEs. This update can help in studies of particle acceleration by shock waves, but it makes recognizing the sources of SPEs still more difficult. Most likely, the events with exceptional flare-acceleration do not exist, because shock waves develop even in eruptive events without detectable microwave bursts, while the escape of accelerated protons from confined flares is hampered. On the other hand, SPEs without powerful flares but with strong shock waves are known. Case studies of selected events of such a kind might shed more light on one of the two sources of SPEs. The results of these studies would provide the guidelines for future statistic analysis.

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